RESEARCH DEPARTMENT

POWER MEASUREMENT IN THE FREQUENCY RANGE 30-1000 Mc/s

Report No. E-054

(1956/22)

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

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SUMMARY

Laboratory equipment has been developed for measuring power over a wide range of levels in the frequency range 30–1000 Mc/s. A milliwattmeter using thermistors measures powers between 1 and 20 mW directly, and its use is extended to higher powers by means of dissipative attenuators and directional couplers. Each item of the equipment is fitted with connectors, suitable for use with 71-ohm coaxial cable. The report also describes a power monitor fitted to v.h.f./u.h.f. transmitters.

1. INTRODUCTION.

The equipment described in this report was developed in order to facilitate an investigation into the propagation of radio waves at frequencies in Bands III, IV and V*. The minimum band of frequencies to be covered was therefore 174 Mc/s to 960 Mc/s, but it was desirable to extend this range to lower frequencies. In fact, the equipment developed is useful between frequencies of 30 and 1000 Mc/s.

In order to investigate the propagation of radio waves, it is necessary to measure both the power radiated by a transmitter and the field strength at a distant point. The mean transmitter power to be measured was between 100 and 300 W. Since the aerial from which this power was to be radiated might not be well matched to its feeder, it was desirable that the method of measurement should not be too sensitive to the reflection coefficient at the load. Measurements of transmitter output power were also necessary in the course of acceptance tests on the transmitters, which were developed by a contractor.

A further requirement was for power monitors to be fitted to the transmitters in order that any change in the radiated power could be noted. Unlike the remainder of the equipment the monitor did not require to be calibrated absolutely; it was sufficient to indicate the relative power on a scale which could be calibrated occasionally.

For calibrating field-strength measuring receivers at very-high and ultra-high frequencies, the only practical methods entail the generation of a known power at a medium or low level. The method in most common use in the B.B.C., which is termed the "standard-field" method, is to radiate a power between 1 mW and 1 W from an aerial. This power could be measured either by substituting a power-measuring device for the aerial, or by the use of a more sensitive method of power measurement in combination with a calibrated directional coupler. The latter method is particularly convenient since it enables the power to be measured while it is being radiated.

*The frequency ranges of these are as follows:

Band III	174 Mc/s–216 Mc/s
Band IV	470 Mc/s–585 Mc/s
Band V	610 Mc/s–960 Mc/s

An alternative method of calibrating field-strength measuring receivers, which is termed the "standard-aerial" method, entails the use of a signal generator. Since reliance cannot be placed upon the absolute calibration of commercial signal generators, a means of recalibration is required. This may be done either by measuring the output power, which is usually less than 100μ W, directly or by generating a known low power for comparison with the signal generator output.

2. REQUIREMENTS.

The powers to be measured fall into three principal ranges:

(i) Transmitter outputs 100-300 W.

(ii) Oscillator outputs 10 mW-1 W.

(iii) Signal generator outputs < 1 mW.

Rather than design a different instrument for each range it was thought preferable to have one power-measuring instrument and to extend its range by means of auxiliary equipment.

The thermistor milliwattmeter was designed to have a range of 1-20 mW, for reasons to be given in Section 3. This range was extended to 0·5 W by means of 2·5 dB, 5·0 dB and 10 dB dissipative attenuators. In addition a 20 dB attenuator was made in order to increase the utility of the attenuators for other purposes.

For the measurement of powers greater than 0·5 W directional couplers are used in conjunction with attenuators. Directional couplers may also be used for the measurement of powers less than 1 mW by the use of a comparison method. In order to reduce the amount of laboratory work only one design of directional coupler was produced, but this was made in three lengths in order to provide different output ratios.

The accuracy required in a measurement of power was 0·5 dB. In order to achieve this result it was necessary, firstly, that the accuracy of the milliwattmeter and of the calibration of the attenuators and directional couplers should be appreciably better than 0·5 dB, and secondly, that the matching of the individual components should be adequate to avoid further errors[1]. This last point requires amplification.

A statement of the power output of a source, such as a signal generator, is not complete until the impedance of the load has been stated. It is therefore essential that apparatus set up for power measurement should present the appropriate impedance to the source. Moreover, the insertion loss of an attenuator depends upon the source and load impedances between which it is connected. It was therefore decided to design all components for the same characteristic impedance, which was chosen to be 71 ohms, a value that has been adopted as standard in view of the availability of a convenient and uniform coaxial cable of this characteristic impedance (Uniradio 21). The accuracy of matching aimed at, and achieved in most cases, was such that the reflection coefficient due to imperfections in any one component should

not exceed 0·05 (standing-wave ratio 0·9). The effect of this permitted degree of mismatch will be illustrated by examples.

Suppose that the milliwattmeter is used directly to measure the power that would be delivered to a resistive load of value R_0 by a source. The error due to departure of the impedance of the milliwattmeter from R_0 would depend upon the impedance of the source. Thus, if the source impedance is itself R_0 the error is $-\frac{1}{4}\%$, but if the source impedance departs from R_0 to the same extent as the milliwattmeter (corresponding to a reflection coefficient of 0·05), the error may have any value between $-\frac{3}{4}\%$ and $+\frac{1}{4}\%$. The error is greatest if the source has an impedance corresponding to unit reflection coefficient, i.e. a very high impedance, a very low impedance, or a reactive impedance. In this case the error could be $\pm 10\%$.

The insertion loss of a dissipative attenuator will be affected by mismatch. For example, if the attenuation is greater than 10 dB, and if the impedance of the attenuator and of the source and load between which it is connected correspond to reflection coefficients of 0·05 relative to R_0, then the insertion loss may vary within a total range of 0·1 dB.

3. THE MILLIWATTMETER.

The milliwattmeter is in two parts:

(i) The thermistor head.

(ii) A form of Wheatstone's bridge which will supply a known amount of d.c. power to the thermistor head and at the same time monitor its resistance.

The resistance of the thermistor head is determined by the total power fed into it and, for a given amount of power, can be made equal to the characteristic impedance of the system. The apparatus is standardised by supplying the whole of this power via the d.c. bridge, which is arranged to indicate balance when the desired impedance is reached. The power is determined by measuring the d.c. voltage across the bridge. When radio frequency power is applied to the thermistors their resistance is further reduced, causing an unbalance to be shown on the indicator of the d.c. bridge. Balance is restored by reducing the d.c. power applied and the amount by which it is reduced is a measure of the applied r.f. power.

The smallest thermistors available were used in order to make the thermal time constant as low as possible and to simplify the problem of matching. It is common practice to operate such thermistors at a power of 1 mW, but at such a low level it is necessary to use an additional thermistor to compensate for drifts of ambient temperature. In order to avoid this complication, the thermistors were run as hot as possible, with a power of about 15 mW each. Drift due to ambient temperature variations was further reduced by mounting the thermistors in a brass block of large thermal capacity.

3.1. The Thermistor Head.

In a device in which it is required to measure a combination of direct and alternating current, decoupling is necessary to prevent the direct current from flowing

through the alternating-current source and vice-versa. Decoupling capacitors present little difficulty, but it would have been difficult to design an r.f. choke to cover the range of frequencies required. For this reason the arrangement shown in Fig. 1, which uses capacitors only, was adopted. Detailed layout and dimensions of the thermistor head are given in Research Department drawing RB.10795.

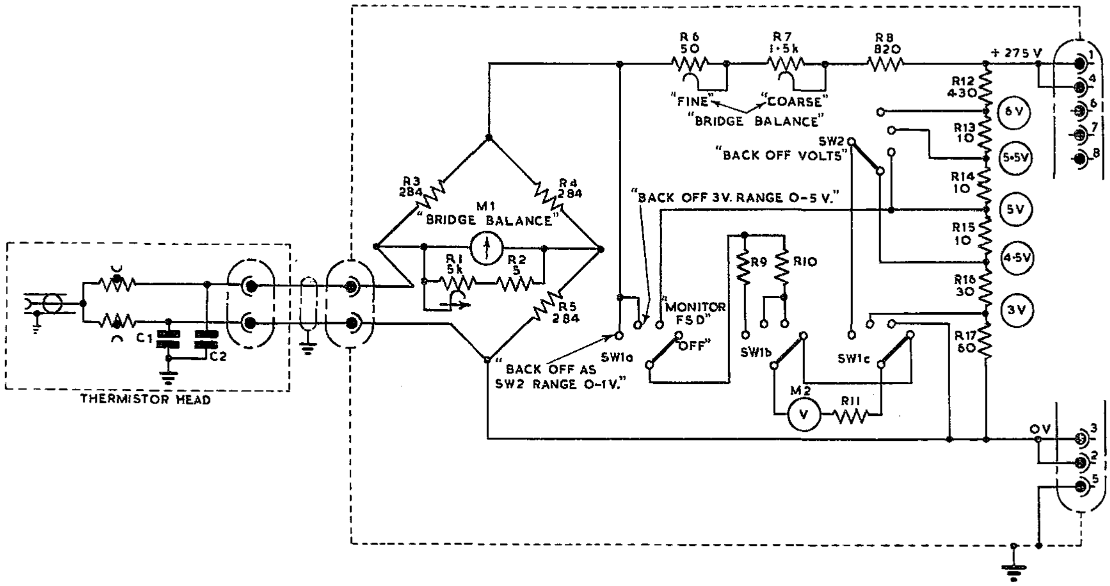


Fig. 1

In this arrangement there are two thermistors (Standard Telephones and Cables type E2361/20), each having a cold resistance of 2000 ohms and a resistance of 60 ohms when dissipating 20 mW. Direct current is applied to the two thermistors in series, while the r.f. power is applied to them as a parallel combination via the capacitors C_1 and C_2. Both terminals of the d.c. supply are thus at earth potential to r.f. and no r.f. power can flow through the d.c. source. Direct current is also prevented from flowing through the r.f. source by making the d.c. power supply "float". This series-parallel arrangement is well known and has been used in waveguide milliwattmeters. Tests of the decoupling in the frequency range 500–1000 Mc/s showed an attenuation of over 40 dB between the r.f. and d.c. inputs. At lower frequencies the effect of stray inductances and capacitances is negligible and the decoupling can be predicted.

The impedance looking into the r.f. socket is required to be 71 ohms, a value considered to be the average characteristic impedance of Uniradio 21 coaxial cable. Accordingly, the Wheatstone bridge must be arranged to maintain the resistance of the series combination at 284 ohms, assuming that C_1 and C_2 have a reactance which is negligible compared with 142 ohms, the resistance required of each thermistor. Since each capacitance is about 350 $\mu\mu$F, this assumption is justified for frequencies above 30 Mc/s.

The practical arrangement of the thermistor head is shown in Fig. 2. The thermistors are assembled in a large block of brass (A), the thermal capacity of which is sufficient to prevent appreciable changes in temperature during the interval of

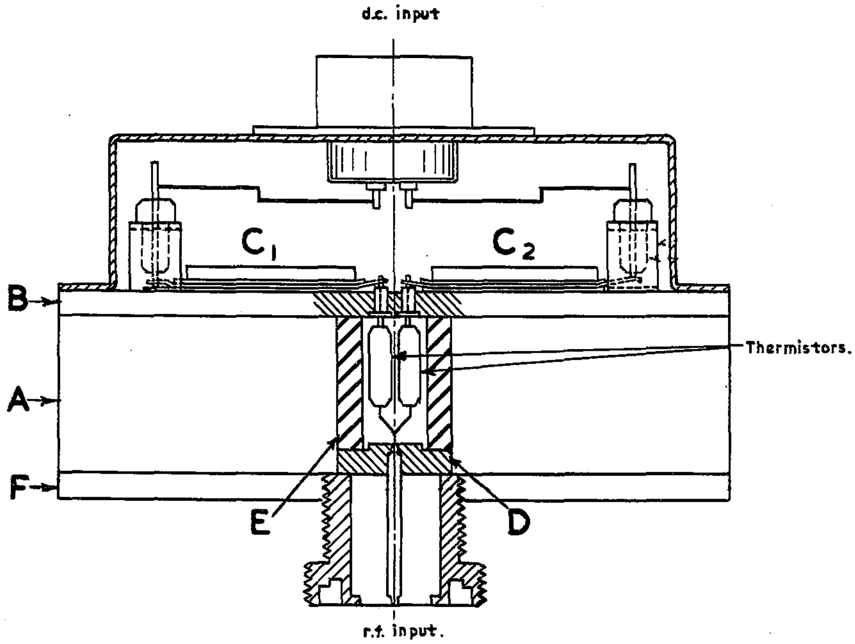


Fig. 2

time between the initial setting up of the d.c. bridge and the actual measurement. Surrounding the thermistors is a brass sleeve (E) whose inside diameter and shape influence the standing-wave ratio of the unit. This sleeve is held between the brass plate (F) which carries the r.f. input socket, and the plate (B) which carries the decoupling capacitors. The capacitors are formed by copper foils clamped down to plate (B) and separated from it by mica sheets 1 mil thick. The thermistors are arranged side by side with their envelopes touching and with their leads connected as shown in Fig. 2. A distrene thrust washer (D) is provided to prevent damage to the thermistors when the r.f. plug is engaged.

The path of the r.f. power, which enters at the Telconnector socket, is through each of the two thermistors and through the capacitors C_1 and C_2 to earth. The direct current is applied to the foil which forms the insulated electrodes of the capacitors and is connected to the end remote from the thermistors. This arrangement, which is electrically equivalent to the well-known "feed-through" capacitor, ensures that the inductance of the leads connecting the thermistors to the capacitors does not contribute to leakage of r.f. into the d.c. circuit.

The admittance looking into the r.f. plug of the thermistor head with the d.c. bridge at balance, was measured at frequencies between 30 Mc/s and 1000 Mc/s. It will be seen from Fig. 3 that the s.w.r. is better than 0·8 over this frequency range.

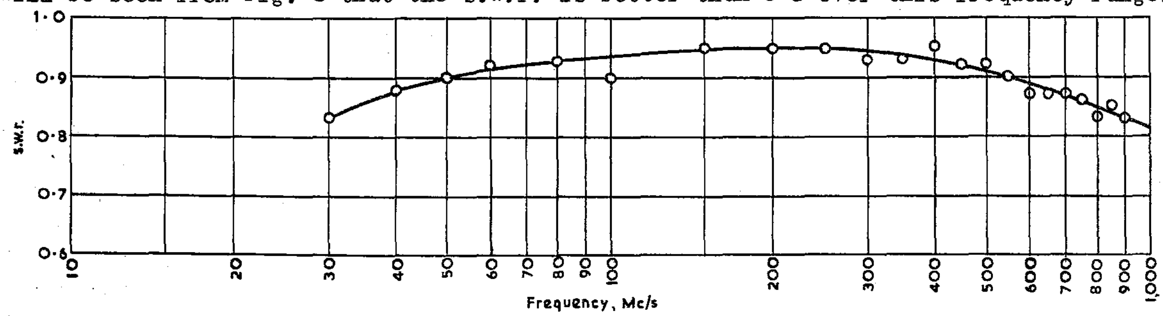


Fig. 3 - Thermistor head—variation of input admittance with frequency

During these measurements the r.f. power entering the thermistor head was kept small for reasons which will be given later.

It is possible that there might be sufficient dissipation in the glass envelope and the leads of the thermistor to introduce an appreciable error at the higher frequencies. The efficiency, η, of the thermistor head may be defined

$$\eta = \frac{P'}{P''}$$

where P' is the power measured in terms of the d.c. calibration and P'' is the incident power. An estimation of η may be made by comparison with some other power measuring equipment[2] or by means of impedance measurements[3,4]. The latter method requires impedance measurements of an accuracy which is difficult to attain.

Lane[2] has obtained values of the efficiencies of thermistors of 0·9 at 3 cm (10 000 Mc/s) and Beatty and Reggia[4] have found a bolometer mount to have an efficiency of 0·98 at 1000 Mc/s. It is thought probable that the efficiency of the thermistor head described is not lower than 0·98 at 1000 Mc/s; a measurement would be desirable if the means became available.

3.2. The D.C. Bridge Unit.

The d.c. potential across the bridge when in the balanced condition and in the absence of any r.f. power input is about 6 volts. However, about 12 volts is needed initially, in order to take the thermistors on to the operational part of their characteristic. In fact a supply of 27·5 volts was used, but only because this was readily available from a stabilised power supply already in existence.

The variable resistors R_6 and R_7 (Fig. 1) provide a coarse and a fine control of the d.c. power fed into the bridge. The power is measured as a function of the voltmeter reading V.

The maximum permitted dissipation is 40 mW (20 mW for each thermistor). The power necessary to bring each thermistor resistance down to the required 142 ohms, is given by the manufacturers as 13 mW each, making a total of 26 mW for the instrument. If this power is applied wholly as d.c. the voltage applied to the d.c. bridge will be at maximum and the indicator sensitivity will be highest. If the power is derived wholly from the r.f. input, there will be no direct current available to operate the indicator. It is evident therefore that a limit of power which the instrument can handle is given by that amount below 26 mW which will leave enough direct current to operate the bridge balance indicator.

In fact it was found that, because of individual variations in thermistor characteristics, a total d.c. power of over 30 mW was required to balance the prototype thermistor head, and with r.f. applied, a balance could still be obtained when the instrument indicated about 26 mW of r.f. power. This, however, is not the true maximum power which it is possible to measure. The arrangement of two thermistors in parallel is unstable since the thermistors are operated in a region of the resistance-current characteristic which has a negative slope. One thermistor tends to take all the current and become low in resistance, while the resistance of the other becomes high. The series arrangement is quite stable provided that the supply has sufficient source impedance. Thus, with the series-parallel arrangement used, there comes a point, as the ratio of r.f. to d.c. power is increased, where the

former takes control and the thermistors become unbalanced. In practice this happens when the r.f. power being dissipated in the thermistors is greater than about 20 mW, and occurs even though the thermistors have been selected for similar characteristics. As the thermistors become unbalanced the match of the thermistor head is degraded, a proportion of the incident power is reflected, and the measurement of power is low. Fig. 4(a) shows the variation of d.c. voltage across each thermistor with increasing r.f. power, and Fig. 4(b) shows the degradation of the match of the thermistor head when the thermistors become unbalanced.

Unfortunately, it may not be apparent that the thermistors have become unbalanced, since a bridge balance may still be obtained. Accordingly, the circuit of the milliwattmeter was arranged so that the d.c. voltage applied to the bridge cannot be reduced below 3 volts. It follows that r.f. powers greater than about 20 mW cannot be measured.

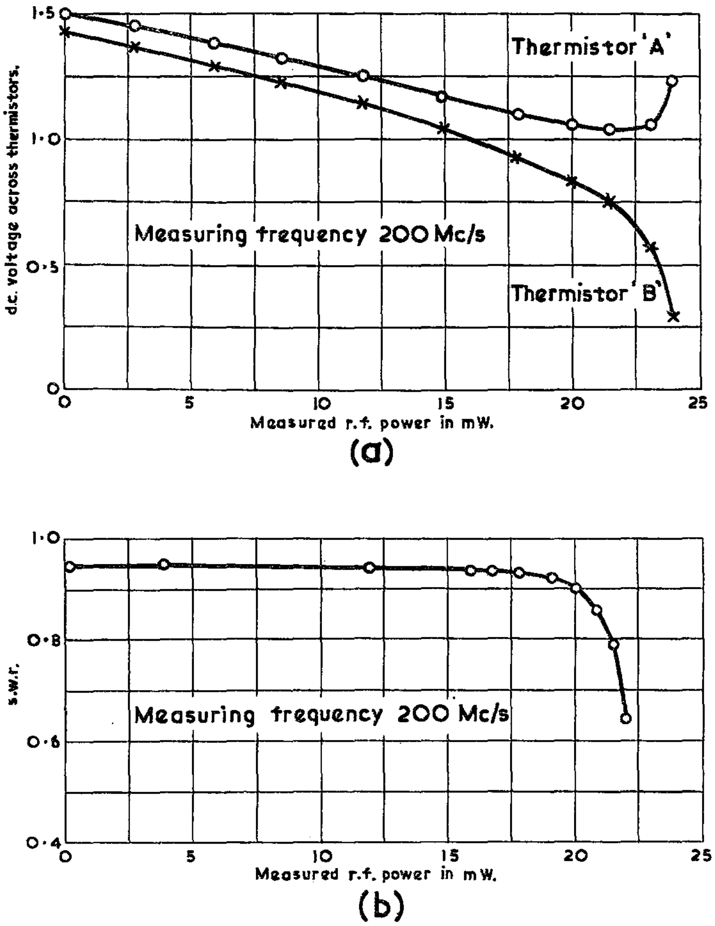


Fig. 4

(a) Unbalance of thermistors with excessive r.f. power

(b) Degradation of match of thermistor head with excessive r.f. power

Since the bridge values are constant and known, the measurement of the d.c. power evolves into the measurement of the d.c. voltage applied to the bridge. This voltage is in the range 3·0–6·3 volts. In order to achieve a sensitivity for the voltmeter which is commensurate with that of the bridge detector, a number of meter ranges are used, each with a backing-off voltage. These ranges are:

(a) 3·0–8·0 volts

(b) 4·5–5·5 volts

(c) 5·0–6·0 volts

(d) 5·5–6·5 volts

(e) 6·0–7·0 volts

These ranges allow for wide variations of thermistor characteristics and ambient temperature.

The backing-off voltage is obtained from a potential divider of high-stability wire-wound resistors, connected across the d.c. supply voltage (Fig. 1). The current in the potential divider is 50 mA and the meter reads full scale when passing 100 μA. Thus the maximum disturbance to the potential divider caused by the meter is 0·2% or 0·011 volts for a backing-off voltage of 5·5 volts.

3.3. Power Supply Unit.

It will be seen that the milliwattmeter requires a d.c. supply which is highly stabilised against load current variations and against variations in the mains supply voltage. Furthermore, the supply should float, i.e. be independent of earth. Frequently, a low resistance to d.c. is put across the r.f. input socket by the r.f. source and if one junction of the bridge is earthed this will amount to a short-circuit across one of the thermistors.

The power unit is an adaptation of the B.B.C. Type SPS/5[5] (Fig. 5). This has an output voltage which may be preset in the range 25–30 volts, and is constant to better than ±0·2% for simultaneous variations of load current from 30 to 80 mA and of mains voltage from 190 to 260 volts r.m.s. Long term stability is better than ±0·2%.

The output was made to float by inserting a "negative line". In order to reduce the voltage at mains frequency appearing across the thermistors, this line was decoupled by a 50-μF 12-volt electrolytic capacitor. A slow d.c. voltage build-up was reduced by the leakage current through the electrolytic capacitor.

3.4. Measurement Procedure.

In Fig. 1 the bridge resistors, R3, R4 and R5, are all nominally 284 ohms and therefore when the bridge is balanced the thermistors assume this value of resistance. If the voltage across the bridge is V, the voltage across the thermistors is 0·500 V and the d.c. power developed in them is

$$\frac{(0{\cdot}5\ V)^2}{284{\cdot}0} = 0{\cdot}880 \times 10^{-3}\ V^2 \text{ Watts}$$

The apparatus is therefore standardised by setting up R6 and R7 for a balance of the bridge and noting the standardising voltage V_s. The r.f. power is then applied and the balance of the bridge is restored by means of R6 and R7. A second reading of the voltmeter, V_m, is noted. The r.f. power is then 0·880 $(V_s^2 - V_m^2)$ mW.

The standardising voltage, V_s, will vary with the particular thermistors used, with time owing to ageing of the thermistors, and with ambient temperature. It is always necessary, therefore, to make a standardising measurement immediately before or after an r.f. measurement.

In an experimental version of the milliwattmeter the resistors R6, R7 and R8 (Fig. 1) were replaced by resistance boxes, and the voltmeter was disconnected. A sensitive spot galvanometer was used as the bridge detector. The voltage delivered by the power unit was measured with a sub-standard voltmeter. Bridge balancing was effected by adjusting the resistance boxes, and a simple calculation gave the d.c.

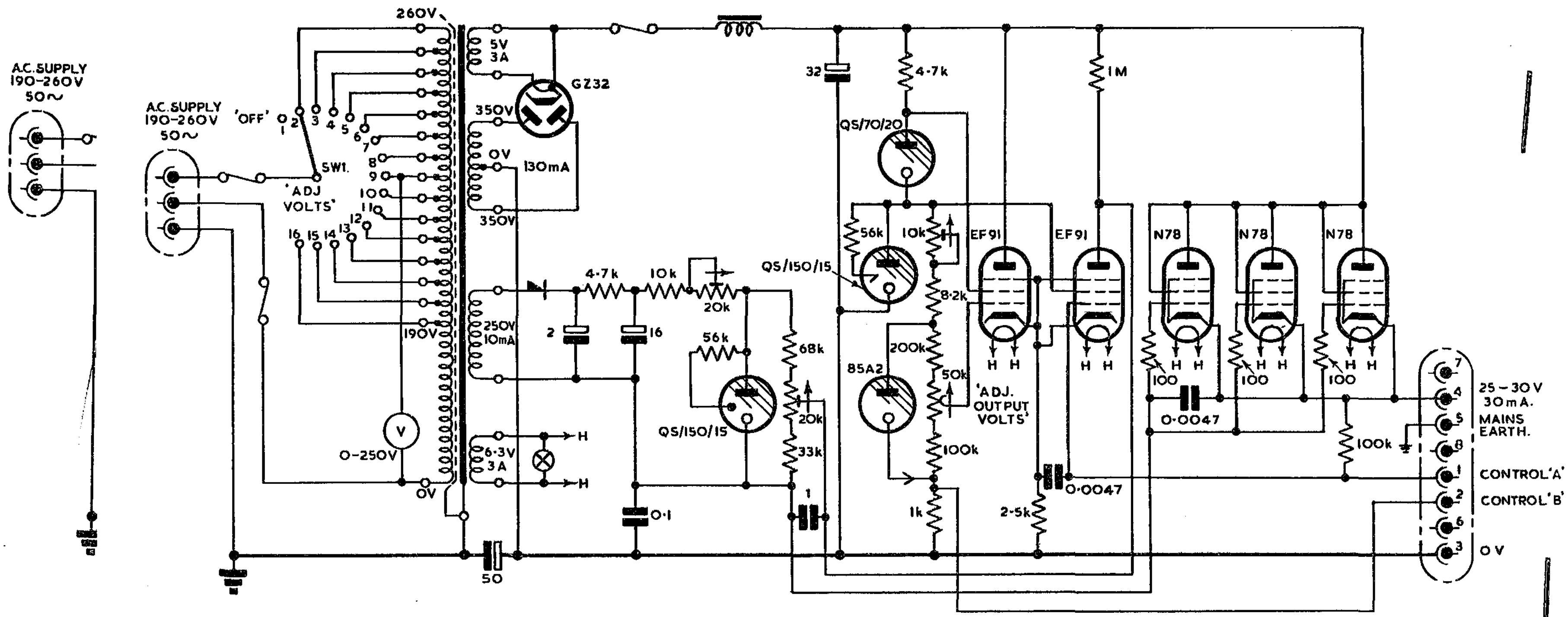


Fig. 5 - 30-volt power supply unit

power being developed in the thermistors. The accuracy of this measurement was ± 1% and accordingly an r.f. power of 15 mW at a frequency between 50 and 500 Mc/s could be measured to an accuracy of ± 2%, assuming a matched source impedance and unit efficiency for the thermistor head. This is comparable with the accuracy of the sub-standard equipment developed by Bailey, French and Lane[6] for the 3 cm and 10 cm wavebands.

The insertion losses of some of the 2·5 dB and 5·0 dB attenuators were measured by means of this form of the milliwattmeter. In this case the applied d.c. voltage need not be known provided it remains constant, and an accuracy of ± 0·05 dB was obtained.

4. THE ATTENUATORS.

4.1. General.

In order to achieve a good match in an attenuator, it is necessary either to make the resistive elements small, thereby making the permitted dissipation small, or to relinquish the property of symmetry. Asymmetrical attenuators have been made[7,8] to accept a dissipation of some 50 W, but the source impedance was not equal to the load impedance, and therefore the latter needed to be very accurately matched.

The attenuators to be described are symmetrical and have been designed to give a compromise between the degree of matching and the power rating. The performance is adequate for the applications envisaged, but it is believed that a more accurate match would have been achieved, or a wider band of frequencies covered, by more careful development and more accurate construction. Attenuators of similar dissipation have been made elsewhere to cover frequencies up to 3000 Mc/s.

Four attenuators were designed having values of 2·5, 5·0, 10·0 and 20·0 dB respectively. To allow convenient resistance values the 2·5 and 5 dB units are single π sections and the 10 and 20 dB units are single T sections. Cracked-carbon film disk and rod resistors are used for the shunt and series elements respectively; their values are given in Table 1. The resistance values have been calculated for an impedance of 71 ohms. A tolerance of ± 1% of the nominal values was allowed.

One prototype of each value of attenuator and about 40 production models have been made.

D.C. measurements made on all attenuators indicated insertion losses within ± 0·1 dB of their nominal values.

TABLE 1

Values of Attenuator Elements

ATTENUATION dB	SHUNT ELEMENTS ohms	SERIES ELEMENTS ohms
2·5	(2) 496·2	20·74
5·0	(2) 253·7	43·19
10·0	49·8	(2) 36·85
20·0	14·33	(2) 58·1

4.2. Layout.

The detailed construction of the attenuators is shown in Research Department Drawings Nos. RG.10815 and RG.10816, and the general arrangements of the π-section and of the T-section are shown in Fig. 6 and Fig. 7 respectively.

The resistors are assembled in metallic sleeves whose inner diameters are chosen for optimum matching. The whole assembly slides into a tubular brass body and is held in position by modified type 53 Telconnectors, one end being fitted with a plug, and the other with a socket. Thrust disks are provided to prevent strain on the resistors when engaging the coaxial connectors. All metallic surfaces are silver-plated.

Some difficulty was encountered due to variations of the physical size of the resistors and it was found necessary to allow for such variations in the design.

4.3. Matching.

Fig. 6 shows the layout of the π-section attenuators. An attempt was made to make the impedance between the planes C and D and between C′ and D′ equal to the impedance seen through the attenuator, but possibly due to the lumped shunt capacitance of the two disk resistors, it was found experimentally that the diameter of the outer at planes D and D′ needed to be rather greater than was expected. The ratio of the diameters between planes E and E′ was approximately that of a lossless line of characteristic impedance 71 ohms. In the case of the 5 dB attenuator it was found experimentally that this also needed to be somewhat higher. To effect this would have involved a considerable change of design and the degradation of the match was therefore accepted.

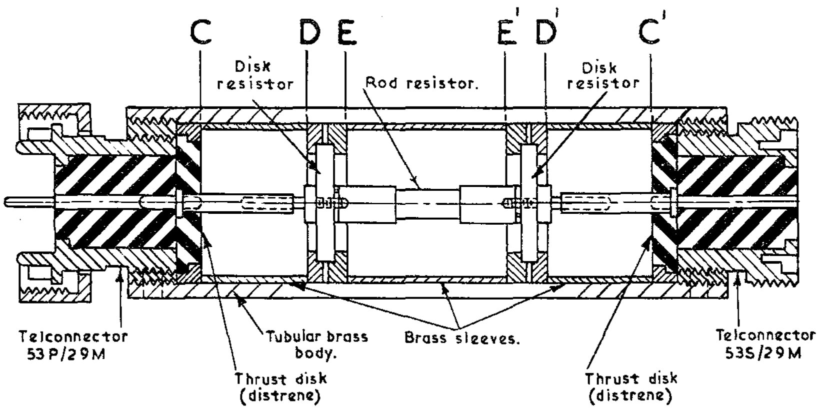


Fig. 6

The layout of the T-section attenuators is shown in Fig. 7. The impedance seen at the disk resistor is equal to the resistance of the disk, shunted by the series combination of the termination (71 ohms) and the rod resistor, and is of the order of 13 ohms for the 20 dB and 34 ohms for the 10 dB attenuator. The ratio of diameters between A and A′ is therefore made to correspond in characteristic impedance to these values. From these planes the inside diameter of the sleeve is increased linearly until the planes BB′ where the ratio of the diameters is the same as in a lossless 71-ohm coaxial line. These planes do not coincide with the ends of the carbon elements in the rod resistors, their position for optimum match being determined experimentally.

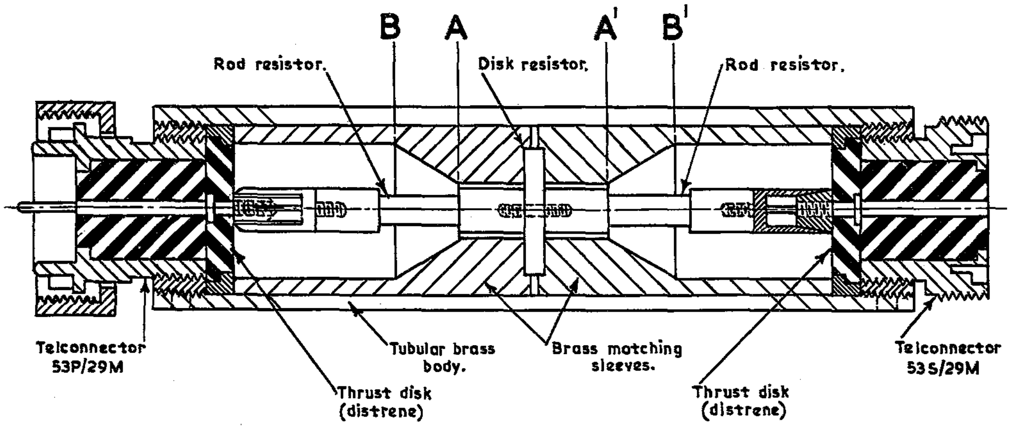


Fig. 7

4.4. Performance.

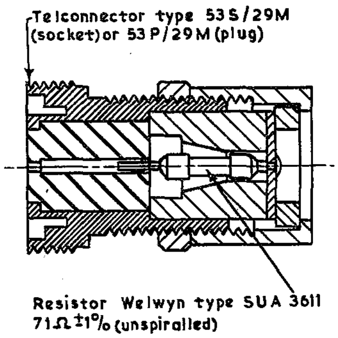


Fig. 8

In order to make impedance measurements, a 71-ohm termination was built into a type 53 Telconnector socket. This embodied a 71-ohm (± 1%) one-eighth watt cracked-carbon non-spiralled resistor. Details of the construction are given in Fig. 8. Measurements of admittance were made with the General Radio Admittance Meter Type 1602B, through a length of Uniradio 21 cable. At frequencies below 500 Mc/s the s.w.r. is better than 0·95, but falls to 0·91 at 900 Mc/s. Other terminations are being developed in order to obtain a better match at higher frequencies.

The measured s.w.r. of the 2·5 dB, 10·0 dB and 20 dB attenuators is better than 0·90 up to 900 Mc/s, when measured with the 71-ohm termination. The s.w.r. of the 5·0 dB attenuators falls to 0·88 at 900 Mc/s.

The attenuation was compared with a piston attenuator at 200 Mc/s and 600 Mc/s, and, in the case of one attenuator of each value, at 700, 800 and 900 Mc/s. In addition, some of the 2·5 dB and 5·0 dB attenuators have been measured by means of the milliwattmeter at 900 Mc/s. The results show that the nominal values of attenuation are maintained within the limits of accuracy of the piston attenuator measurement, namely ± 0·3 dB. The more accurate milliwattmeter measurements indicated for the 2·5 dB and 5·0 dB attenuators an increase in value of 0·2 dB at 900 Mc/s.

4.5. Power Rating.

The rod resistors used have a nominal rating of ¼ W. There is no published information on the rating of the disk resistors, but an estimate has been made by comparing the surface areas of the rods and disks. The maximum power ratings of the attenuators calculated on this basis are given in Table 2.

TABLE 2

Maximum Dissipation of Attenuators

Attenuator	Terminated in (71 + j0) ohms	Terminated in s/c or o/c
2·5 dB	1·2 W	0·75 W
5·0 dB	0·8 W	0·60 W
10·0 dB	0·48 W	0·44 W
20·0 dB	0·31 W	0·30 W

Ratings of the 2·5 dB and 5·0 dB attenuators may be therefore taken to be 0·5 W, and those of the 10 dB and 20 dB attenuators to be 0·25 W.

An attempt was made to verify the theoretical ratings experimentally, tests being made on one attenuator of each value. One end of the attenuator was terminated in 71 ohms and a d.c. voltage applied at the other end. The results were approximate, but tended to confirm the theoretical ratings. They also indicated that these ratings could be exceeded by 100% without very much degradation of the match or permanent damage to the attenuator. Such treatment would, of course, be unwise when the attenuator is used as a standard.

5. DIRECTIONAL COUPLERS[9].

5.1. General.

A directional coupler is a device for sampling waves travelling in either direction along a transmission line or waveguide. In general it has two pairs of terminals for connection to the transmission line and two auxiliary outputs. The directional couplers to be described are symmetrical, i.e. there is no distinction between the terminals intended for connection to the main transmission line and those of the auxiliary outputs.

It is convenient to represent a symmetrical directional coupler by the symbol shown in Fig. 9(a). A_1, A_2, B_1, B_2, each represent a pair of terminals suitable for connection to a transmission line. In Fig. 9(b) three of the pairs of terminals are terminated in pure resistances equal to the characteristic impedance of the transmission line for which the directional coupler has been designed (this will be termed the characteristic impedance of the directional coupler) and the fourth (A_1) is connected to a generator. Part (usually the greater part) of the r.f. power passes along the straight line A_1 A_2, into the load at A_2, but a proportion of it passes along the curved line A_1 B_1 into the auxiliary load at B_1. If the ratio of the power

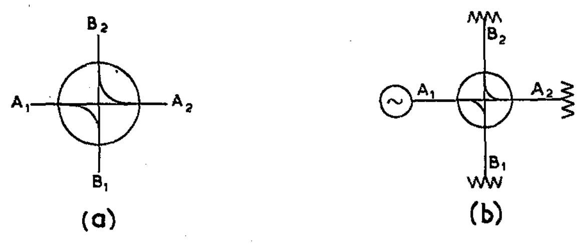


Fig. 9

(a) Symbol representing a symmetrical directional coupler

(b) Action of a directional coupler

supplied to the load at B_1 to that supplied to the load at A_2 be denoted by K^2, K may be termed the *output ratio* of the directional coupler. If the directional coupler is perfect and if the loads at A_2 and B_1 are perfectly matched to its characteristic impedance, no power is supplied to the load at B_2. Imperfection of the directional coupler in this respect may be expressed in terms of the *directivity*, the ratio of the output at B_1 to that at B_2, normally expressed in decibels.

A symmetrical directional coupler having perfect directivity has the following properties:

(i) Referring to Fig. 9(b), the input impedance at A_1 is perfectly matched, provided that the loads at A_2 and B_1 are matched.

(ii) The outputs at A_2 and B_1 are in phase quadrature.

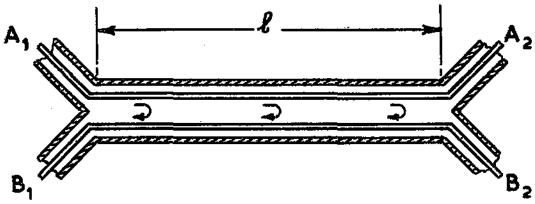


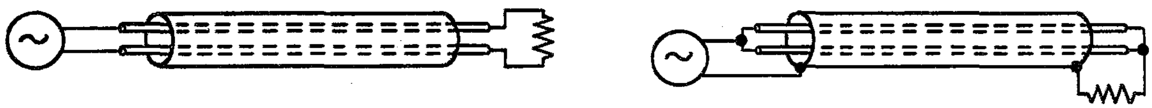
Fig. 10 - Coupled transmission lines

The directional couplers to be described consist of two unbalanced transmission lines, which are coupled together by sharing a common outer conductor (Fig. 10) so as to form, in effect, a three conductor transmission line. Symmetry has been ensured by making the two inner conductors identical in form and disposition.

The output ratio varies sinusoidally with frequency, being a maximum when the effective length of the three-conductor line is an odd number of quarter-wavelengths.

5.2. Theoretical Considerations.

Figs. 11(a) and 11(b) show a symmetrical three-conductor transmission line excited as a balanced and an unbalanced two-conductor line respectively. Let the



(a) (b)

Fig. 11 - Three-conductor line

(a) As a screened balanced transmission line, characteristic impedance $2\ R_b$

(b) As an unbalanced transmission line, characteristic impedance $\frac{1}{2}\ R_u$

characteristic impedance be $2\ R_b$ for the balanced line and $\frac{1}{2}\ R_u$ for the unbalanced line. It will be evident that R_u and R_b differ only by reason of the coupling between the inner conductors. It can be shown that the three-conductor line behaves as a symmetrical directional coupler whose characteristic impedance, R_o, is given by

$$R_o \quad = \quad \sqrt{(R_u\ R_b)} \tag{1}$$

provided that the velocity of propagation is the same for both the unbalanced and the balanced modes of excitation shown in Fig. 11. This last condition might not be satisfied if the dielectric were not uniform.

It is convenient in view of Equation 1 to express R_u and R_b as

$$R_u = kR_o \tag{2}$$

$$R_b = R_o/k \tag{3}$$

where k is a parameter which must be greater than unity; its departure from unity is a measure of the coupling between the inner conductors. The output ratio K has been shown[9] to be given by

$$K = \tfrac{1}{2}(k - 1/k)\ \sin\beta l \tag{4}$$

where βl is the angular length.

5.3. Experimental Work.

5.3.1. The Prototype.

In the first place it was necessary to choose a cross-section for the 3-conductor line to satisfy Equation 1. Once this was achieved, it remained to design the ends so as to ensure that discontinuities and stray coupling would not impair the directivity.

The cross-section of the 3-conductor line was determined by measurements at 1 Mc/s using a series impedance bridge. At this frequency stray capacitances may be ignored, but skin and proximity effects are substantially complete. Specimen inner conductors were mounted inside the square-section outer sheath and were short-circuited to it at one end. The current terminals of the bridge were connected to the outer conductor and to one of the inner conductors. A screened voltage probe was passed through small holes in the upper cover-plate at known distances from the short-circuit, and the self and mutual inductances per unit length were measured.

The internal impedance of the conductors, which is negligible at very high frequencies, could not be neglected completely at 1 Mc/s. A small correction was therefore made for its effect on the measured inductance by observing the measured resistance and using the fact that, when the skin depth is small in comparison with the smallest dimension of the conductors, the internal resistance and internal reactance are equal. This correction was applied to both the self-inductance and mutual-inductance measurements.

The impedances, R_u, R_b, were deduced from the inductance measurements. The dimensions and spacing of the inner conductors were adjusted until $\sqrt{(R_u\ R_b)}$ was as near to 71 ohms as could be measured, while ensuring that the parameter $k = \sqrt{(R_u/R_b)}$ was sufficiently large to give the required maximum output ratio. With the finally selected cross-section k was 1·46. This value indicated a maximum output ratio of 0·39 (−8·2 dB).

It remained to match the ends of the three-conductor line into 71-ohm coaxial cable. This was done by observing the directivity at u.h.f. and adjusting the ends of the three-conductor line until an adequate performance was obtained.

The final arrangement is shown in Fig. 12. The two inner conductors are

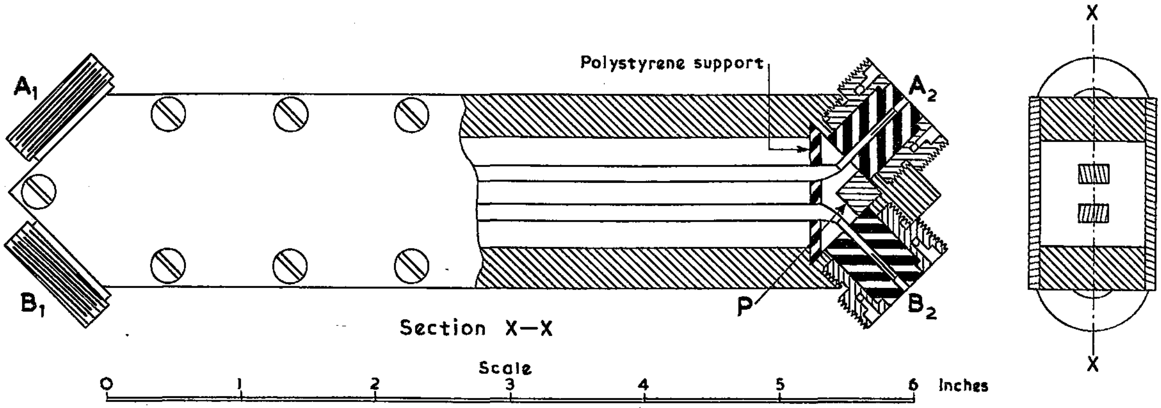


Fig. 12 - Final form of prototype

each of rectangular cross-section and are supported in the square-section outer conductor by slotted polystyrene plates. Immediately beyond the polystyrene the inner conductors are bent outwards at 45°, and are tapered to join the inner conductors of Type 53 Telconnector sockets. Square section brass blocks, P, were inserted at each end, their dimensions being chosen for optimum directivity.

5.3.2. Measurement of Directivity.

In the early stages of adjustment, when the directivity was below about 25 dB, it was possible to terminate the outputs at A_2 and B_1 (Fig. 9(b)) and adjust for minimum output at B_2. As the performance of the coupler was improved, it was observed that the voltage component appearing at B_2, due to imperfect directivity, became comparable with the components reflected from the terminations which were themselves imperfect. A different technique was therefore necessary. This was as follows.

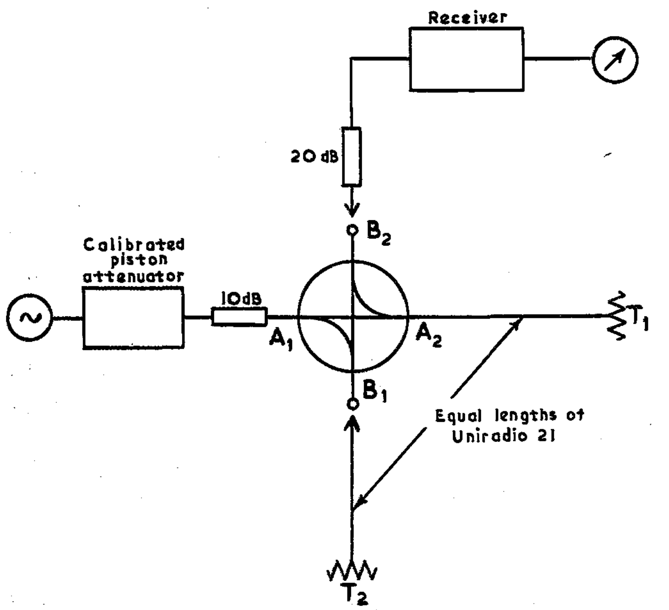


Fig. 13 - Measurement of directivity — practical arrangement

Two relatively poorly matched terminations were connected to the directional coupler through equal lengths of about one metre (3·3 ft) of Uniradio 21 cable. The voltage components due to reflections at the terminations thus arrived at B_2 (Fig. 13) with a phase relation which was independent of frequency. The component arising from imperfect directivity, however, varied cyclically in phase relative to the other two, with a smaller amplitude. Thus a plot against frequency of the output at B_2 relative to that at B_1 showed a ripple, the amplitude of which was a measure of the true directivity.

Fig. 14 illustrates some of the measurements. The upper curve relates to measurements made

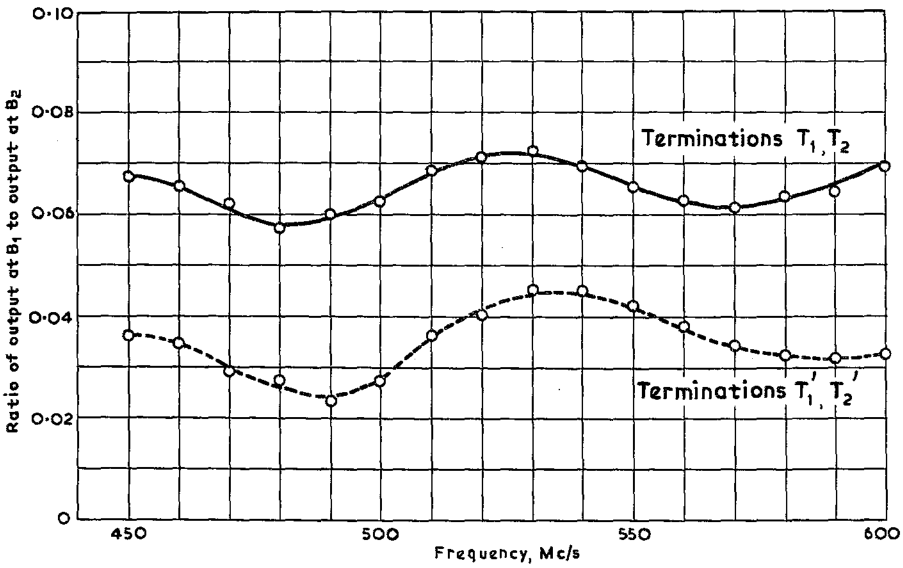


Fig. 14 - Measurements of directivity on prototype directional coupler

using two terminations T_1 and T_2. These terminations were replaced by others, T_1', T_2' of different values and the measurements were repeated. These are shown in the lower curve. It will be seen that the height of the curve is changed but that the amplitude of the ripple is not, demonstrating that the latter arises from imperfect directivity rather than reflection from the terminations.

A directivity of about 35 dB, at frequencies between 100 Mc/s and 900 Mc/s, was obtained with the prototype. Directivities higher than this were not attainable because of lack of uniformity in the cable.

5.3.3. Measurement of Output Ratio.

For these measurements power ratios were determined directly, using the thermistor milliwattmeter in the arrangement shown in Fig. 15. At each frequency measurements were made both of the power passing straight through the directional coupler as well as that at the secondary output.

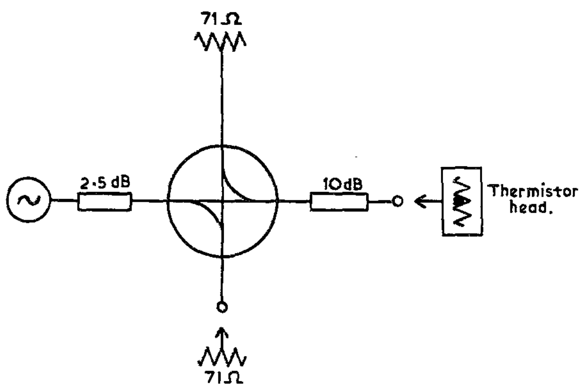


Fig. 15 - Measurement of output ratio using milliwattmeter

In order to reduce the ratio of power to be measured, a 10 dB attenuator (calibrated separately) was connected in series with the principal output of the directional coupler. A 2·5 dB attenuating pad at the output of the oscillator was inserted to make the source impedance more nearly 71 ohms, and so to reduce any error due to mismatch of the 10 dB attenuator.

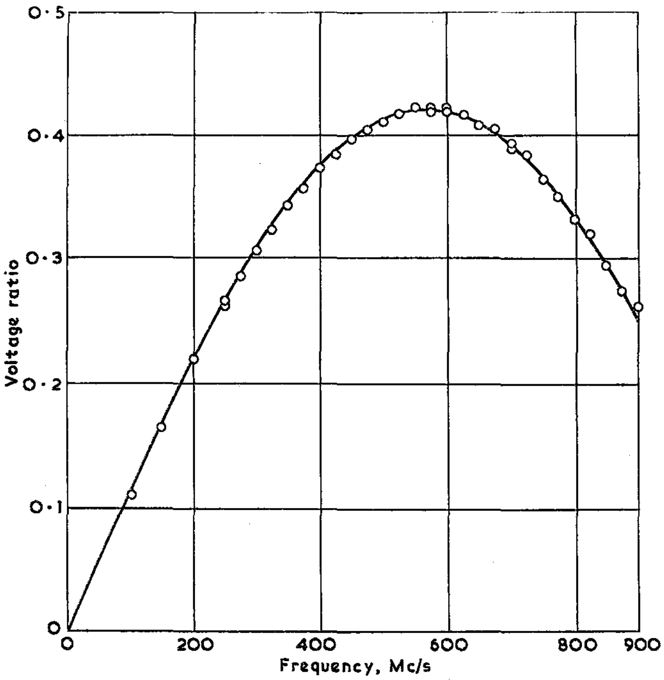


Fig. 16 - Output ratio of prototype directional coupler

The results of measurements over the frequency range 100–900 Mc/s are plotted in Fig. 16, together with the sine curve which gives the best fit. It will be seen that the maximum output ratio is 0·42, compared with the value 0·39 deduced from the low-frequency inductance measurements. This discrepancy is attributed to error in measuring the small mutual inductance between the inner conductors.

5.4. Development of Other Models.

On the basis of the work with the prototype, three modified directional couplers were produced. These had the same cross-section, and the same end matching as the prototype, but differed in the lengths of the three-conductor section.

It was considered desirable to have output ratios of approximately −10 dB, −20 dB and −30 dB at 200 Mc/s. The three versions were therefore designed to have maximum coupling at about 350 Mc/s, 1250 Mc/s and 4000 Mc/s respectively. Four directional couplers of each length were produced. Unfortunately, production errors resulted in the dimensions of the end-matching arrangement being slightly different from those of the prototype, and the resulting directivity was found to be below the requirements. In order to keep additional work to a minimum, the inner conductors were modified to compensate for errors in the outer casing. The resulting directivity tended to vary with frequency, but was not less than 26 dB over the required frequency range.

The shortest of the three versions of the directional coupler had too great an output ratio for the measurement of the higher powers in Bands IV and V. The lead-cable directional couplers described in Section 6.2 were used for this purpose.

6. POWER MONITORS FOR V.H.F./U.H.F. TRANSMITTERS.

6.1. General.

Six transmitters, two for each of the three Bands III, IV and V, have been obtained from a contractor for investigating radio-wave propagation. The greater part of this work is carried out using square-wave modulation at 1000 c/s, the mean powers being 300 W, 200 W and 100 W in the three frequency bands respectively. The transmitter outputs are fed through about 300 m (1000 ft) of HM7 coaxial cable to a high-gain aerial. The feeder loss varies from 4 dB in Band III to 9 dB at the upper end of Band V.

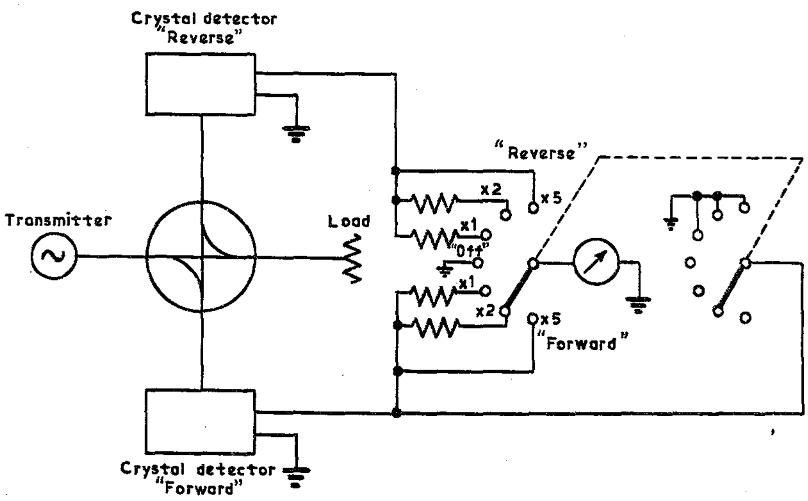


Fig. 17 - General arrangement of power monitor

A power monitor was required to give a direct reading of the transmitter power without undue sensitivity to harmonics, or to small changes in the impedance of the aerial. In addition, it was desirable to have some indication of any failure of the aerial or feeder.

The monitor provided consists of a directional coupler which feeds a sample of both the power flow towards the aerial and that reflected from it into matched crystal detectors (Fig. 17). The monitor is calibrated by means of the thermistor milliwattmeter described in Section 3.

6.2. The Directional Coupler.

An output ratio of about 0·03 (−30 dB) was required. A high directivity was not essential, 20 dB being considered adequate. It was found possible to meet these requirements with a directional coupler which was much simpler than that described in Section 5.3.

Two lead-covered polythene-filled cables (Uniradio 25) were each milled to form a flat surface. The cut extended into the polythene dielectric, which was exposed in a slot. They were then clamped together with the slots coincidental, and the outer conductors soldered. The slots were necessarily tapered at each end where the cables were bent away from the flat surface, but this was in any case considered desirable, since the discontinuities caused by rectangular ends would be expected to impair the directivity. Sufficient measurements were made to check that an adequate directivity was obtained, but it did appear that the directivity was less than predicted theoretically[9], possible owing to end effects.

The length of each directional coupler was arranged to be about one quarter-wavelength at the operating frequency, in order to reject even harmonics. Odd harmonics would be accepted only to the same extent as the fundamental. For each band the value of the output ratio was chosen to deliver a mean power of about 300 mW to the "forward" detector with the transmitter operating at full power. The measured output ratios were in good agreement with an approximate theoretical prediction[9].

6.3. The Crystal Monitor.

The auxiliary outputs of the directional coupler are taken to two crystal monitors, the "forward" and "backward" monitors. In each case the power is dissipated in terminations of approximate match and crystals are used to indicate the r.f.

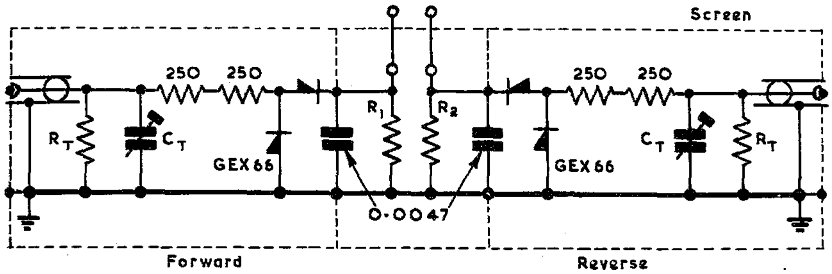


Fig. 18 - Circuit arrangement of crystal detectors

voltage appearing across these terminations (Fig. 18). It is, of course, necessary that non-linearity in the crystals should not upset the matching arrangement, and this is ensured by inserting two 250-ohm resistors in series with each crystal. The terminations are built up on Telconnector sockets type 53C, and use four resistors in a series-parallel arrangement, in order to reduce the effect of capacity between the end caps. These are indicated by R_T in Fig. 18. C_T gives a fine adjustment of reactance. All the resistors used in the r.f. circuits are of unspiralled cracked-carbon.

In order to correct for imperfect directivity of the directional coupler, the "forward-power" termination is adjusted so that the reading of reflected power is zero when the transmitter feeds into a matched 71-ohm load.

By means of switched series resistors, three possible sensitivities are provided, giving meter readings in the ratios of 1, 2 and 5. The crystal load resistor, R_1 (of the order of 300 ohms), in the forward monitor, is chosen to give a reading of approximately 0·8 of full scale in the one-to-one range when the transmitter is developing full power. The corresponding resistor in the backward monitor, R_2, is given a higher value (2·5 kΩ) in order to obtain greater sensitivity.

One meter is used for observation of both the forward and the backward powers, and a seven-position switch provides the three sensitivities for each monitor, with an off position. In order to prevent d.c. interaction through the directional coupler, a second wafer on the switch arranges for the d.c. output of the forward monitor to be short-circuited while the meter is reading the reflected power.

Both forward and reflected power monitors are calibrated under the same modulation conditions as used by the transmitter (1:1 square waves) by means of the power-measuring equipment.

6.4. Performance.

The output of the transmitters normally has to traverse 300 m (1000 ft) of feeder before reaching the aerial. The sensitivity of the power monitor to the match of the aerial is therefore restricted by the attenuation and possible lack of uniformity of the feeder. Fortunately, the feeder is reasonably uniform, but the attenuation results in the sensitivity to a given aerial mismatch falling off as the frequency increases. In practice, however, the monitors on the Band III and Band IV transmitters have given useful indications of faults on the aerials, and have proved of value in diagnosing the presence of ice.

7. MEASUREMENT TECHNIQUES.

7.1. Powers Greater Than One Quarter Watt.

The source of power is connected through one arm of a directional coupler, either to the load into which it will normally work (e.g. an aerial), or to a dummy load which is capable of dissipating the power and which presents a reasonable match to the line (Fig. 19). A long length of cable may conveniently be used for the higher powers although at some frequencies a poor match may be obtained due to feeder irregularities.

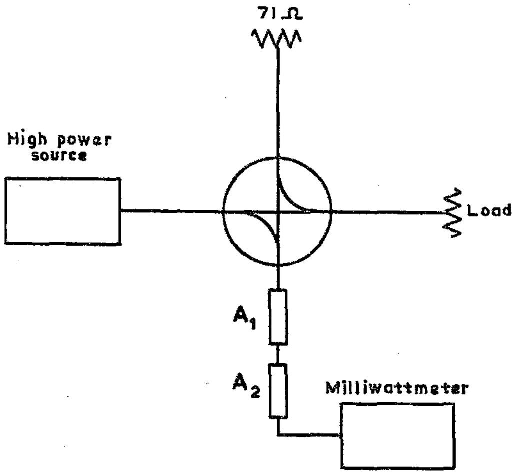


Fig. 19 - Measurement of powers greater than one quarter Watt

The directional coupler should be chosen so that the coupled output is between 1 and 250 mW. If necessary, attenuators A_1 and A_2 (Fig. 19) can be used to bring the power level down into the range of the milliwattmeter. The fourth connector of the directional coupler should be terminated during a measurement. If required, this termination and the milliwattmeter may be interchanged and a measurement made of any power reflected by the load.

7.2. Powers Less Than a Milliwatt.

A comparison method is used. A source of power at a convenient level is measured by the milliwattmeter and simultaneously attenuated by means of a directional coupler and fixed attenuators, until it is equal to the unknown power. The practical arrangement is shown in Fig. 20. The output of the oscillator is reduced by the attenuator A_1 to a level which is convenient for measurement (10–20 mW). The secondary output of the directional coupler is reduced by attenuators A_2, A_3 to give a level which is near that of the unknown. Fine adjustment to equality is made at the oscillator, and for this purpose the output of the oscillator should be continuously variable over a range of about 3 dB.

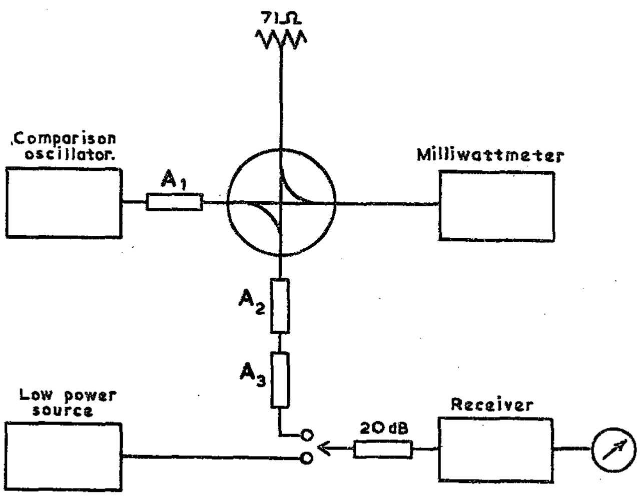


Fig. 20 - Measurement of powers less than one milliwatt

Comparison of the two levels is achieved with a suitable receiver working through a 20 dB matching attenuator. In order to avoid dependence upon the characteristics of the receiver, it is necessary that the frequency and modulation of the oscillator should be the same as the source to be measured.

8. CONCLUSIONS.

Equipment capable of measuring powers from very low levels up to several hundreds of watts has been developed for use in the v.h.f./u.h.f. bands. It is now possible to measure and monitor transmitter output powers, to lay down standard fields for the calibration of receiver stations, and to standardise the outputs of signal generators in the frequency range 30–1000 Mc/s. The component parts of the equipment have also a number of general laboratory applications.

With the exception of the directional couplers, the components described have been designed in accordance with accepted practice, and contain no new features. Their development was necessary only because suitable equipment was not available commercially.

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